RELATION OF STRENGTH OF WOOD TO DURATION OF LOAD

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Summary

This report presents, for the use of structural engineers, a mathematical expression for an important structural property of wood, the relation of its bending strength to the duration of load. The relationship is mathematically defined, and applications in working-stress problems are shown. Structural designers are thus enabled to take full advantage of the unusually high bending strength of wood under short-time loading.

Data showing the relationship are from recently completed tests of small, clear Douglas-fir beams under long-time load and from earlier studies of rapid loading and impact. An empirical hyperbolic equation is developed to represent the trends of the data. A few exploratory tests of other species and in other strength properties indicate that the relationship may be of general application.

Introduction

Designing engineers customarily set working stresses for structural materials at levels below the yield point, or elastic limit, to insure safe and satisfactory structures under service loading. They recognize that materials loaded beyond the elastic limit may lose elasticity and take on characteristics of brittleness or plasticity, according to their nature. It is less generally known that materials differ widely in this respect, and that in some the strength properties are greatly affected by the duration of loading. Wood has a property valuable to the structural designer in that both its elastic limit and its ultimate strength are higher under short-time than under long-time loading; this permits higher working stresses where live loads of comparatively short duration must be considered in structural design.

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[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

The relation of the strength of wood to the duration of load has been investigated at the Forest Products Laboratory for many years. Recent analysis of duration data from a series of long-time loading tests of small, clear Douglas-fir beams led to a restudy of the relation of duration of load to the strength of wood and a revision of conclusions previously held. This paper summarizes the data considered in the restudy and reports the conclusions reached.

Data considered here are from bending tests of Douglas-fir at two levels of moisture content, both in the air-dry range. The conclusions cannot yet be extended to other species and strength properties or to wood in the green condition, although a few exploratory tests indicate that bending and other strength properties in some other species are similarly affected. Any general application of the conclusions is subject to revision as more complete information is obtained.

Sources of Data

A series of 126 long-time loading tests of 1- by 1-inch, clear Douglas-fir beams at 6 and 12 percent moisture content was begun in 1943 and is now approaching completion. Test specimens were subjected to constant loads ranging from 60 to 95 percent of the loads that caused failure of matched control specimens in a standard static-bending test of about 5 minutes' duration. Durations until failure under these loads ranged from a few minutes to more than 5 years. Figure 1 shows durations plotted against stress levels corresponding to the applied loads in each of the tests. Duration values are shown on a logarithmic scale.

Studies of the effects of rapid rates of loading on small, clear Douglas-fir beams were reported by Liska[2]. Data from that report and a line showing their trend are plotted in figure 2. The time scale is logarithmic. The data of figure 1 and figure 2 are not exactly comparable, since figure 1 shows durations of stress increasing to predetermined levels and then held constant, while figure 2 shows times of loading continuously increasing at a constant rate until failure. Nevertheless, it is believed that both sets of data are governed by the same properties of the material and should be represented by one continuous curve.

Impact tests, in which the actual forces or loads were observed, were reported by Elmendorf[3]. The data indicated that the modulus of rupture of Douglas-fir is about 75 percent greater in impact than in static bending as shown by the standard 5-minute test. Elmendorf's data on Douglas-fir

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[2]Liska, J. A. Effect of Rapid Loading on the Compressive and Flexural Strength of Wood. Forest Products Laboratory Rept. No. R1767. 1950.

[3]Elmendorf, Armin. Stresses in Impact. Journal of the Franklin Institute. Vol. 182. No. 6, 1916.

did not show durations of stress but included results on one specimen of southern yellow pine for which the duration in the same kind of impact test was about 0.015 second. This duration, while not directly connected to the 175-percent strength level, indicates the high stresses that can be developed under extremely rapid loading.

Relation of Duration of Load to Strength

In figure 1, a straight line drawn by eye represents the trend of the data in the long-time loading tests. This line was published in a report by Wood[4] and has since appeared with a modified scale of stress percentages in several other publications. Figure 2 shows a straight line representing the trend of the data from rapid-loading tests. The two straight lines and a single point representing Elmendorf's impact data are converted to the same scale and plotted together in figure 3. Here also the duration scale is logarithmic.

It is evident in figure 3 that both the rapid-loading and the impact data lie above the extension of the straight line representing the long-time loading data, and that the impact point lies above the extension of the line representing rapid loading. A curve representing all of these data cannot be a straight line.

The straight line of figure 1 implies that strength values decrease without limit as the duration is prolonged. This is obviously impossible, since strength cannot have a value less than zero. Experiments with wood in this and other countries indicate that there is probably a threshold strength level somewhere above zero for which the duration is infinite.

From this evidence, it appears that the over-all strength-duration relationship could well be approximated by a hyperbolic curve. The horizontal asymptote of such a curve would represent a threshold strength for which duration is infinite. The vertical asymptote would be at zero time, though there is admittedly no proof that the strength becomes infinite as zero time is approached.

Several attempts at curve-fitting showed that a hyperbola that represented the trends of data in long-time loading and rapid loading could not be passed through the point representing the impact loading. Each of these trends is supported by many tests, while the impact point is related to only one test. A curve was therefore chosen to fit the trends of the two large groups of tests and to pass as closely as possible to the impact point.

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[4] Wood, L. W. Behavior of Wood under Continued Loading. Engineering News-Record. Vol. 139, No. 24, 1947.

Figure 3 shows an empirical hyperbolic curve passing through a point representing a duration of stress of 0.015 second and a stress equal to 150 percent of ultimate strength in a standard test. This curve approximates the trends of data from the long-time-loading and the rapid-loading tests. It has the equation

$$y = \frac{108.4}{x^{0.04635}} + 18.3$$

in which x is the duration of stress in seconds and y is the stress expressed as a percentage of the standard-test strength. This equation is computed so that the curve passes through three selected points. The first point is the point just described and is somewhat below the impact point. The second point is at the 100-percent strength level, for which a duration of stress of 7-1/2 minutes was assumed. The third point is arbitrarily selected from the long-time loading data with a strength level of 69 percent and a duration of 3,750 hours (shown on fig. 1). The horizontal asymptote of this hyperbola is 18.3 percent, a strength level for which the duration is presumed to be infinite.

The hyperbolic curve of figure 3 is also shown on figure 1. It is well within the range of the long-time loading data, though toward the upper side of that range for strength levels of 65 percent and lower. On the other hand, a similar curve for bending strength of Sitka spruce[5] shows still higher strength levels for this range of durations (fig. 1). The departure of the hyperbola from the general trend of data at the 95-percent strength level is necessary to fit it to the rapid-loading data of figure 2. In the absence of similar information from other species, this hyperbola may be taken to express a general relationship between strength and duration of load for those species most used in construction.

Application to Working Stresses

The relation of duration of load to strength is important in the determination of working stresses for structural design with wood. Advantage may be taken of the increased strength of wood under short-time loading by increasing the working stresses where maximum load is of limited duration. Figure 4 illustrates a convenient means for doing this. It shows the hyperbolic curve of figure 3 plotted in a form directly applicable to working-stress use. Basic working stresses recommended by the Forest Products Laboratory are for the condition of long-time full load, for which the strength is assumed to be nine-sixteenths of the strength in the standard 5-minute test. This long-time load level is taken as 100 percent in figure 4 with other percentages calculated from it as a base. Duration values are converted to units of time that are easily visualized for long as well as short durations.

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[5] Forest Products Laboratory. Strength and Related Properties of Wood Grown in the United States. U. S. Dept. of Agr. Tech. Bull. No. 479. 99 pp. Illus.

In the "National Design Specification for Stress-grade Lumber and Its Fastenings," revised 1950, recommended by the National Lumber Manufacturers Association for application to permanent structures, a condition designated as "normal loading" is selected as the basis for working stresses in structural design. The same condition is assumed in the commercial grading rules for stress-graded lumber. "Normal loading" contemplates that the full maximum design load will have a continuous or cumulative duration of not more than about 10 years during the life of a permanent structure. It will be seen in figure 4 that 10-year duration warrants an increase of about 10 percent above the long-time load level. The National Design Specification gives working stresses that contain the 10 percent increase, with provision for removing that increase in cases where the full maximum load is applied permanently or for many years. That basis for working stresses conforms to the principle of adjustment for duration of load.

Maximum working stresses for roof structures in certain areas may be based on expected snow loads. For example, the duration of the greatest expected snow load in temperate climates may be considered by the designer to be only a matter of days, weeks, or at the most a few months during the expected life of the structure. Figure 4 indicates that an increase of about 25 percent over the long-time load level can be made in this instance. This is equivalent to an increase of about 15 percent above the "normal-loading" level.

In like manner, a designer may wish to assume that the maximum horizontal load, as from wind or earthquake, will have a duration not exceeding a matter of minutes or hours during the expected life of the structure. For this condition, a working stress may be 50 percent above the long-time load level or about one-third above the "normal-loading" level.

When applying design stress increases for short-time loading, care should be taken that the sizes of structural members are adequate for the dead or long-time portion of load at a safe long-time working stress. This is accomplished by comparing the working stresses required for a member at each load level and its expected duration. The larger of the working stresses governs the design of that member.

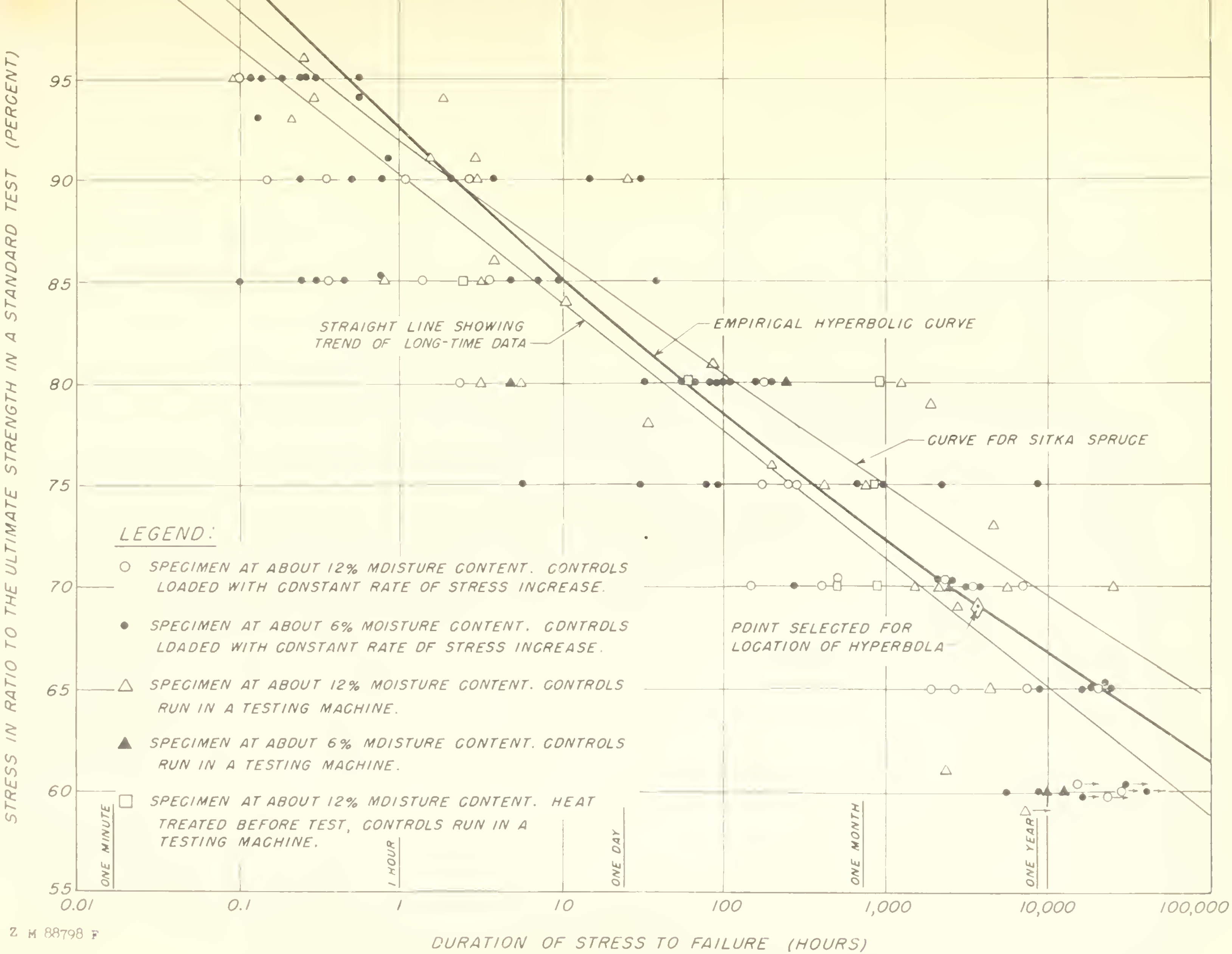

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Figure 1.--Relation of duration of constant stress to level of stress in long-time loading of Douglas-fir bending specimens.

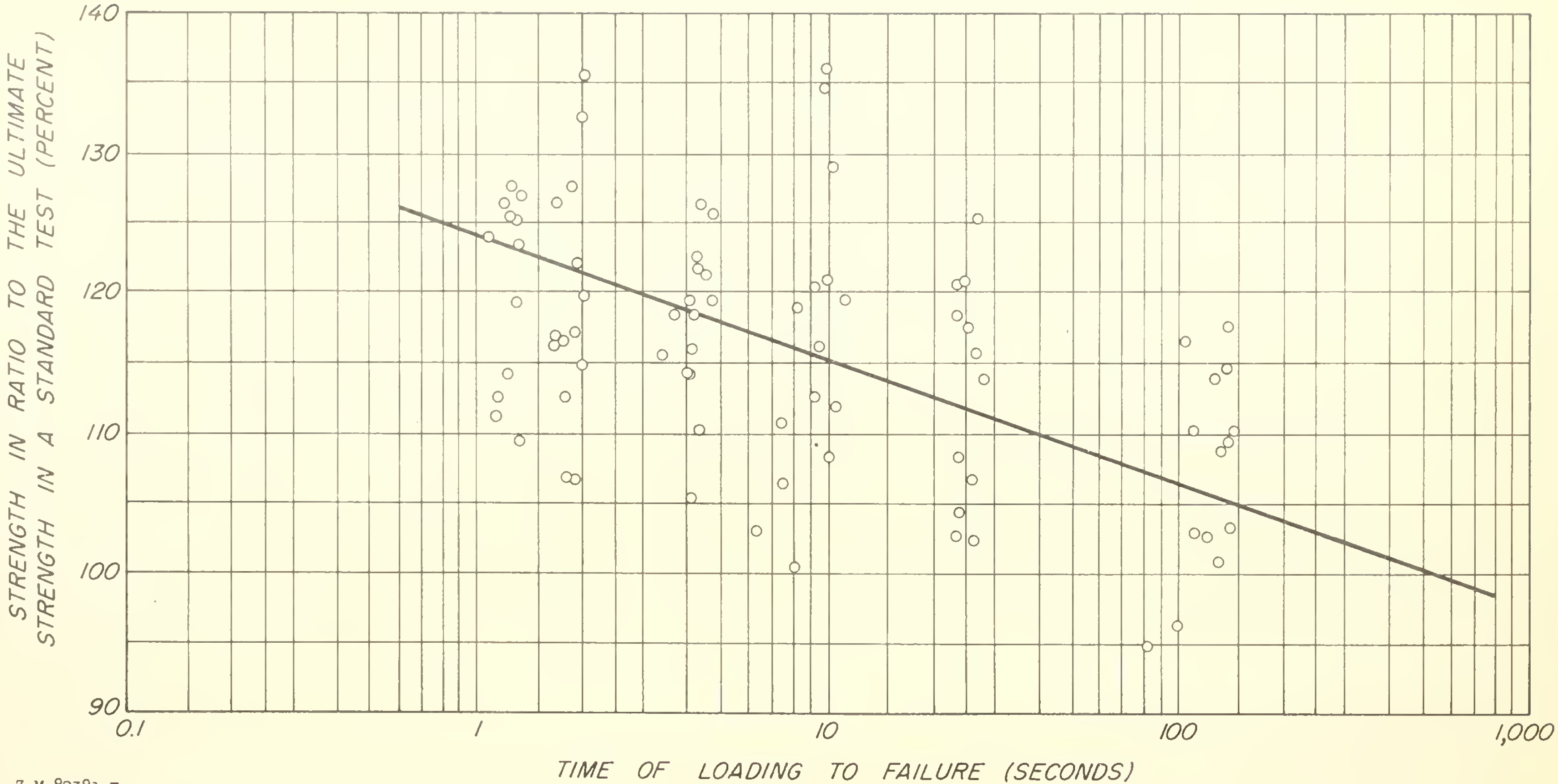

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Figure 2.--Relation of strength to time of loading in rapid-loading tests of small, clear Douglas-fir bending specimens.

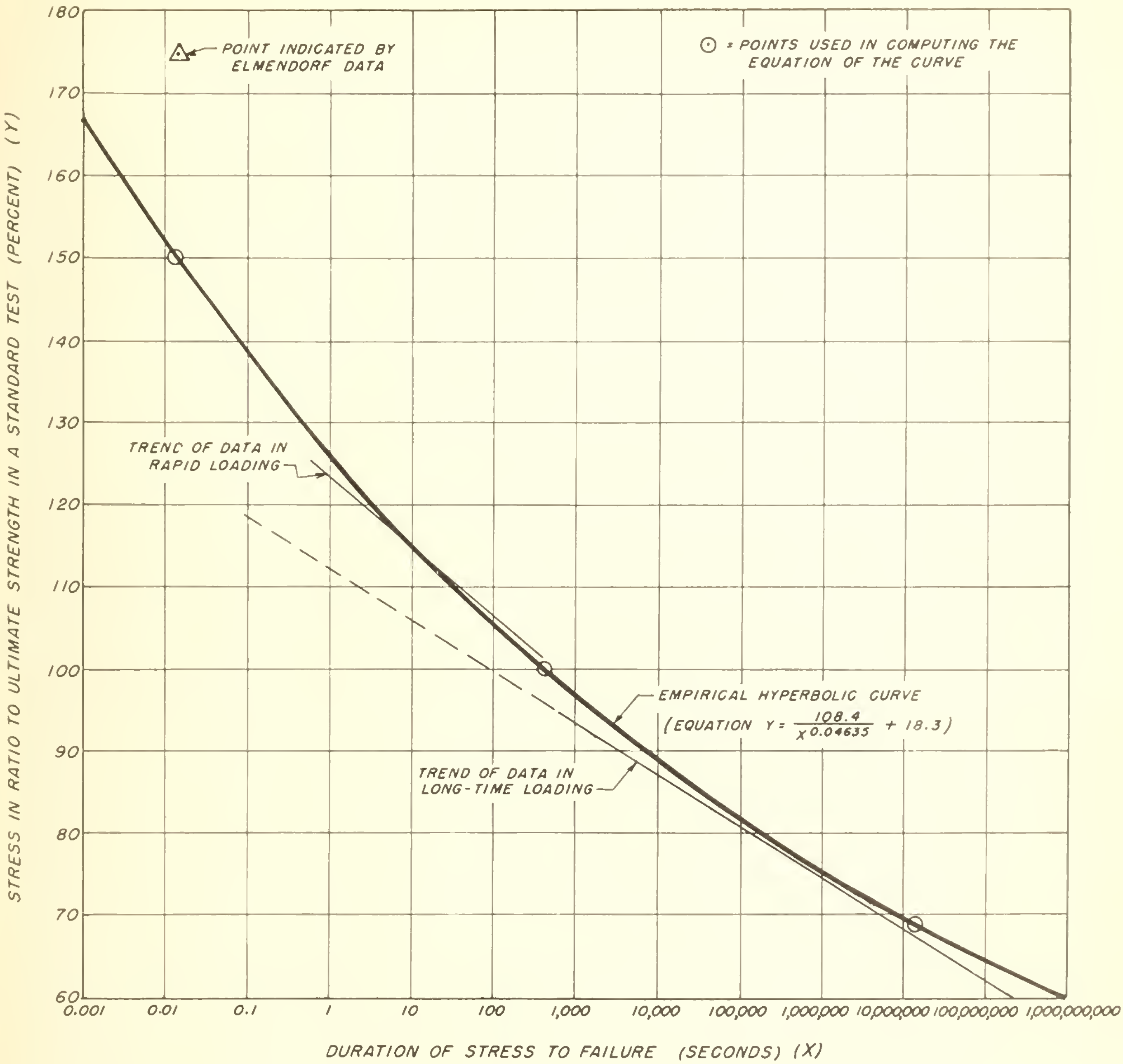

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Figure 3.--Relation of duration of stress to level of stress in long-time loading and rapid loading of Douglas-fir bending specimens. The broken line represents an extension of the curve for long-time loading.

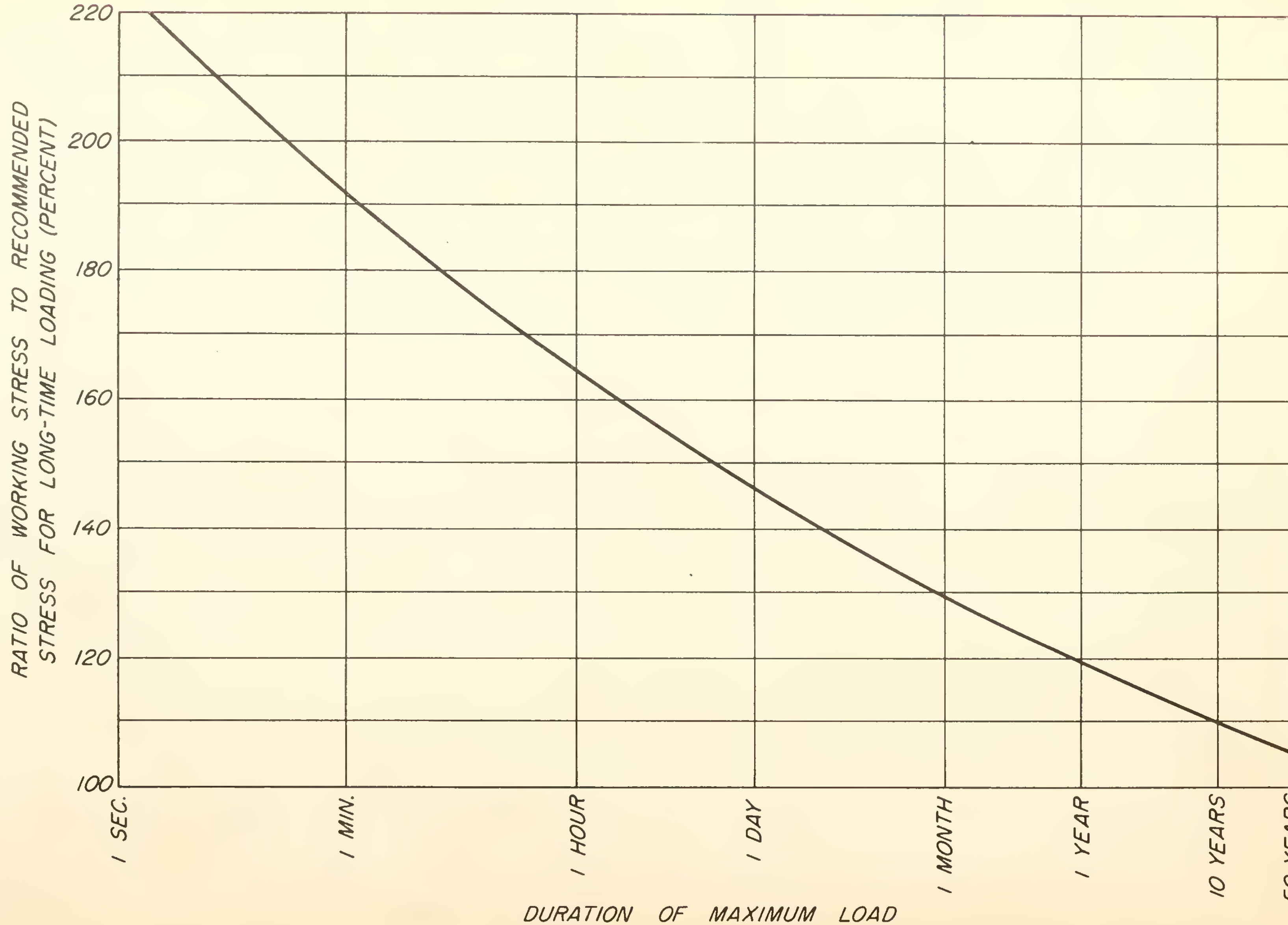

Figure 4.--Relation of working stress to duration of load.